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FINAL REPORT

"Mass Transfer Cooling in Nitrogen and Carbon-Dioxide Gas Streams"

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This is to summarize the major research results of the mass transfer program sponsored by the National Aeronautics and Space Administration covering the highlights of the program from its inception at the University of Delaware in March, 1963, to its conclusion at the University of Illinois at Chicago Circle in June, 1967.

The research activity may be divided conveniently into three major categories:

1) Analytical Studies of Mass Transfer Cooling

2) Experimental Studies of Mass Transfer Cooling

3) Studies of Radiation-Convection Interaction with Mass Transfer

Analytical Studies of Mass Transfer Cooling

The major objective of the analytical studies of mass transfer cooling was the development of a simple design procedure for the prediction of heat transfer and skin friction for mass transfer cooled zero pressure gradient surfaces exposed to the high velocity laminar flow of foreign gases (i.e., free streams other than air).

At the outset, the study was restricted to nitrogen or carbon-dioxide free streams with the injected coolant being hydrogen. Initially, the laminar Couette flow model, a one-dimensional model of the actual boundary layer, was analyzed, taking into account viscous dissipation and variable fluid properties, to give insight into the physics of the binary flow problem. Further, it was hoped that results from the Couette flow study could be used to predict actual boundary layer behavior. The Couette flow analysis was followed by a thorough investigation of the actual two-dimensional binary laminar boundary layer under zero pressure gradient conditions and including the effects of viscous dissipation. Comparisons of the Couette flow results with those found in actual boundary layer situations suggest that a simple design method based on the Couette flow model is not possible.

An alternate approach, based on the work of Gross et al, was then attempted. To accomplish this the hydrogen-nitrogen and hydrogen-carbon-dioxide binary boundary layer results were extended to include results for the following binary gas combinations:

$$CO_2\text{-}N_2,\ CO_2\text{-}H_2,\ CO_2\text{-}CO_2,\ H_2\text{-}H_2$$

These studies were then compared with other analytical information available in open literature. It was found possible to present the normalized Stanton number, St_o, as a function of a generalized blowing parameter yielding a presentation which should have wide utility for the prediction of heat transfer to high velocity zero pressure gradient surfaces in the presence of mass transfer for any combination of free stream and injection gases, provided the boundary layer is laminar.

Inasmuch as the presentation is normalized with respect to the solid wall Stanton number, St_o, it is essential that this value be readily obtainable. In the course of the investigation, it was shown that the Eckert reference formulation applies to high speed boundary layers of air, of nitrogen, of carbon-dioxide and of hydrogen, and it is recommended that this method be used for any free stream gas. The details of this design procedure are spelled out in the attached TR Report entitled "Transpiration Cooling Correlations for Air and Non-Air Free Streams" by Simon, Hartnett, and Liu.

Thus, the major results of this portion of the study may be summarized as follows:

1) The Couette flow model does not yield acceptable prediction of actual binary boundary layer behavior.

2) The Eckert reference formulation may be used to predict solid wall heat transfer for the laminar flow of any free stream gas over a flat plate.

3) A simple design presentation of the heat transfer, skin friction and recovery factors for a mass transfer cooled flat plate in high velocity laminar motion applicable to any free stream gas and injection gas combination is possible, as presented in the above mentioned reference.

Additional details on the above may be found in the following reports or publications:

1) "Mass Transfer Cooling in Laminar Boundary Layers with Hydrogen Injected into Nitrogen and Carbon Dioxide Streams," C. S. Liu, J. P. Hartnett, and H. A. Simon, Proceedings of the Third International Heat Transfer Conference, August, 1966, American Institute of Chemical Engineers, Vol. III, pp. 15-22.

2) "Properties of Hydrogen: Nitrogen and Hydrogen: Carbon Dioxide and Carbon Dioxide: Nitrogen Mixtures," H. A. Simon, C. S. Liu, and J. P. Hartnett, NASA Contractor Report 387, February, 1966, (also published in shorter form in the International Journal of Heat and Mass Transfer, Pergamon Press, Vol. 8, No. 8, 1965, pp. 1176-1178).

3) "The Eckert Reference Formulation Applied to High Speed Laminar Boundary Layers of Nitrogen and Carbon Dioxide," H. A. Simon, C. S. Liu, and J. P. Hartnett, International Journal of Heat and Mass Transfer, Pergamon Press, Vol. 10, No. 3, 1967, pp. 406-409, (also published as NASA Contractor Report 420, April, 1966).

4) "Influence of Dissociation on Mass Transfer Cooling in a Carbon Dioxide-Nitrogen Binary System," C. S. Liu and J. P. Hartnett, submitted to Journal of Heat Transfer, A.S.M.E. and scheduled for presentation at the Ninth Heat Transfer Conference, August 6-9, 1967, Seattle, Washington.

5) "Transpiration Cooling Correlations for Air and Non-Air Free Streams," H. A. Simon, J. P. Hartnett, and C. S. Liu, University of Illinois at Chicago Circle, Department of Energy Engineering, Technical Report No. 8, June, 1967, (also submitted to A.S.M.E. for possible presentation and publication).

In addition, the following Masters and Doctoral dissertations were prepared under the partial support of the program:

1) M.S. Thesis - C. L. Chang, "Binary Couette Flow with Hydrogen Injected into Carbon Dioxide and Nitrogen Streams," University of Delaware, June, 1963.

2) M.S. Thesis - C. S. Liu, "Mass Transfer Cooling in Laminar Boundary Layers with Hydrogen Injected into Nitrogen and Carbon Dioxide Streams," University of Delaware, June, 1965.

3) Ph.D. Thesis - C. S. Liu, "Influence of Dissociation on Mass Transfer Cooling in a Carbon Dioxide-Nitrogen Binary System," University of Delaware, June, 1967.

Experimental Studies of Mass Transfer Cooling

The experimental portion of the program involved the determination of the heat transfer for a transpiration cooled porous flat plate placed in turbulent streams of air and of carbon dioxide at a Mach number of approximately 2. The coolant gases were also air and carbon dioxide giving four combinations: air-air, carbon dioxide-carbon dioxide, carbon dioxide-air, air-carbon dioxide. It was found that Rubesin's air to air semi-empirical theory adequately predicted all of the experimental heat transfer results including those obtained in the carbon dioxide atmospheres.

Additionally, the empirical theories which predict recovery factor results for air injected into an air free stream yield satisfactory results for air or carbon dioxide injection into a carbon dioxide free stream gas. A more detailed report on this study ("Mass Transfer Cooling on a Porous Flat Plate in Carbon Dioxide and Air Streams" by Laganelli and Hartnett) is attached.

An optical method developed for obtaining binary diffusion coefficients yielded preliminary results which were in fair agreement with existing information. This method, which shows promise, needs further refinement before accurate and reliable results can be consistently obtained.

Further details on these experimental studies can be found in the following publication:

1) "Mass Transfer Cooling on a Porous Flat Plate in Carbon Dioxide and Air Streams" by A. L. Laganelli and J. P. Hartnett.

In addition, the following dissertations are available:

1) M.S. Thesis - E. Dingilian, "Concentration and Ordinary Diffusion Coefficient Measurements Using Infrared Absorption Technique," University of Delaware, June, 1966.

2) Ph.D. Thesis - A. Laganelli, "Mass Transfer Cooling on a Porous Flat Plate in Carbon Dioxide and Air Streams," University of Delaware, June, 1966.

Studies of Radiation-Convection Interaction with Mass Transfer

In parallel with the variable property pure convection mass transfer studied, a constant property analysis of the radiation-convection interaction problem in the presence of mass transfer was carried out. Again, the initial model for analysis was mass transfer cooling in high-speed Couette flow of an absorbing-emitting grey gas. Upon completion of this study, a constant property analysis of the actual two-dimensional boundary layer on a flat plate was carried out. Finally, the interaction of convection and radiation in axisymmetric and stagnation point flows with mass transfer was treated.

The Couette flow studies demonstrated that the radiation component of the total heat transfer is relatively uninfluenced by the presence of mass transfer but very much influenced by the optical properties of the fluid. On the other hand, the convective heat transfer is relatively insensitive to the optical properties but very sensitive to mass transfer.

The initial boundary layer study treated a mass transfer cooled flat plate placed in an absorbing-emitting high velocity gas stream and exposed to a constant heat input. Two limiting cases were studied: (a) black surface and (b) perfectly reflecting surface. The emphasis was placed on the recovery or adiabatic wall case where conduction to the wall is balanced by radiation from the surface. Equilibrium wall temperatures are reported over a wide range of operating variables.

Recently, the boundary layer interaction studies have been extended to two-dimensional and axisymmetric stagnation flows. It is found that an appropriate choice of the governing dimensionless parameters allows the presentation of the temperature distribution and the heat transfer for these two flows such that there is nearly a one-to-one correspondence. An important conclusion from this work is that the influence of the absorption coefficient is very sensitive to the magnitude of the wall emissivity. For high wall emissivities the total heat transfer decreases with increasing absorption coefficient. On the other hand, for low wall emissivities the overall heat transfer increases with absorption coefficient to a maximum value and then decreases as the absorption coefficient is further increased.

These results are contained in the following publications:

1) "Mass Transfer Cooling in High Speed Couette Flow of an Absorbing-Emitting Gas," J. L. Novotny, Y. Taitel, and J. P. Hartnett, Proceedings of the 1965 Heat Transfer and Fluid Mechanics Institute, Stanford University Press, June, 1965, pp. 71-86.

2) "Equilibrium Temperatures of Mass Transfer Cooled Walls in High Speed Flow of an Absorbing-Emitting Gas,", J. L. Novotny, Y. Taitel, and J. P. Hartnett, Proceedings of the Third International Heat Transfer Conference, August, 1966, Chicago, Illinois, American Institute of Chemical Engineers, Vol. V, pp. 138-145.

3) "Equilibrium Temperatures in a Boundary Layer Flow over a Flat Plate of an Absorbing-Emitting Gas," Y. Taitel and J. P. Hartnett, University of Illinois at Chicago Circle, Department of Energy Engineering Technical Report 1, September, 1966 (to be published in the Journal of Heat Transfer of A.S.M.E.).

4) "Interaction of Convection and Radiation in an Axisymmetric and Two-Dimensional Stagnation Point Flow," N. A. Macken and J. P. Hartnett, Proceedings of the 1967 Heat Transfer and Fluid Mechanics Institute, June, 1967, Stanford University Press, pp. 115-139.

In addition, the following dissertations are available:

1) Ph.D. Thesis - Y. Taitel, "Equilibrium Temperatures in Flow of an Absorbing-Emitting Gas," University of Delaware, June, 1966.

2) Ph.D. Thesis - N. A. Macken, "Interaction of Convection and Radiation in an Axisymmetric and Two-Dimensional Stagnation Point Flow," University of Delaware, March, 1967.